Eur. Phys. J. C (2011) 71:1744
DOI 10.1140/epjc/s10052-011-1744-9

THE EUROPEAN
PHYSICAL JOURNAL C

Letter

Search for diphoton events with large missing transverse energy with 36 pb^{-1} of 7 TeV proton–proton collision data with the ATLAS detector

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Received: 4 July 2011 / Revised: 12 August 2011 / Published online: 5 October 2011

Abstract Making use of 36 pb^{-1} of proton–proton collision data at $\sqrt{s} = 7$ TeV, the ATLAS Collaboration has performed a search for diphoton events with large missing transverse energy. Observing no excess of events above the Standard Model prediction, a 95% Confidence Level (CL) upper limit is set on the cross section for new physics of $\sigma < 0.38$–0.65 pb in the context of a generalised model of gauge-mediated supersymmetry breaking (GGM) with a bino-like lightest neutralino, and of $\sigma < 0.18$–0.23 pb in the context of a specific model with one universal extra dimension (UED). A 95% CL lower limit of 560 GeV, for bino masses above 50 GeV, is set on the GGM gluino mass, while a lower limit of $1/R > 961$ GeV is set on the UED compactification radius R. These limits provide the most stringent tests of these models to date.

1 Introduction

In high-energy proton–proton (pp) collisions, Standard Model (SM) production of diphoton ($\gamma\gamma$) events with two prompt photons and large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) is due primarily to W/Z production with the associated electroweak production of two photons. Taking into account the branching ratios of W/Z decays that include at least one neutrino, the cross sections for events with large transverse energy (E_{T}) photons are well below 100 fb for 7 TeV pp collisions. In contrast, some new physics models predict much larger $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ yields. This Letter reports on the search for $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ events with 36 pb^{-1} of ATLAS data collected in 2010, extending a prior study [1] performed with 3.1 pb^{-1}. The results are interpreted in the context of a general model of gauge-mediated supersymmetry breaking (GGM) [2–4] as well as a model positing one universal extra dimension (UED) [5, 6].

2 Supersymmetry

Supersymmetry (SUSY) [7–13] introduces a symmetry between fermions and bosons, resulting in a SUSY partner with identical quantum numbers (differing by half a unit of spin) for each SM particle. At the Large Hadron Collider (LHC), the dominant SUSY process would be the production of pairs of SUSY partners of quarks (squarks) or gluons (gluinos) via the strong interaction. These would then decay through cascades involving other sparticles until the lightest SUSY particle (LSP) is produced. Assuming R-parity conservation [14, 15], the LSP is stable and escapes detection.

No SUSY partners of SM particles have been observed yet, indicating that SUSY must be broken to decouple the masses of the SM particles and their SUSY partners. In gauge-mediated SUSY breaking (GMSB) models [16–22] the LSP is the gravitino $\tilde{G}$. GMSB experimental signatures are largely determined by the character of the next-to-lightest SUSY particle (NLSP), which for most of the GMSB parameter space is the lightest neutralino $\tilde{\chi}_1^0$. Should this neutralino be the SUSY partner of the U(1) gauge boson (the "bino"), the final decay in the cascade is dominated by $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, with two cascades per event, leading to a final state $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}} + X$, where $E_{\mathrm{T}}^{\mathrm{miss}}$ results from the escaping gravitinos and X represents SM particles emitted in the prompt cascade decays.

Previous searches for GMSB [23, 24] were performed using a minimal GMSB model [25]. To reduce the number of free parameters in this model, several assumptions are made, including gaugino mass unification. These assumptions lead to a mass hierarchy in which squarks and gluinos are much heavier than the lightest neutralino and chargino. For example, the current lower limit on the minimal GMSB neutralino mass of 175 GeV [24], based on the assumption of direct production of charginos and neutralinos and obtained

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for the large integrated luminosity accumulated at the Tevatron, corresponds to gluino and squark mass limits in the TeV range. The data analysed in this Letter have a limited sensitivity to the minimal GMSB model and do not improve upon the current Tevatron limits.

In the following a GGM SUSY model [2–4] is considered for which the gluino and neutralino masses are treated as free parameters. The other sparticle masses were fixed to ∼1.5 TeV, leading to a dominant production mode at $\sqrt{s} = 7$ TeV of a pair of gluinos that would decay via cascades into the neutralino NLSP. The NLSP was taken to be the bino-like neutralino, decaying promptly ($c\tau_{\mathrm{NLSP}} < 0.1$ mm) into a photon and a gravitino. The branching fraction to $\gamma\tilde{G}$ is almost 100% for low neutralino masses and approaches $\cos^2\theta_W$ for neutralino masses well above the Z mass. The Higgsino mass term, μ, was set to 1.5 TeV and the ratio of the two Higgs vacuum expectation values, $\tan\beta$, to 2. Similar parameter values were used in the only previous study of this model, in which the CMS experiment excluded signal cross sections between 0.3 and 1.1 pb at 95% Confidence Level (CL) and determined limits on the squark, gluino and neutralino masses [26]. These limits derive from the copious production expected for accessible colour-charged sparticles (squarks, gluinos), and benefit from the increased collision energy even for relatively low integrated luminosity, extending the reach of the LHC beyond that of the current Tevatron data [4].

3 Extra dimensions

UED models [27] postulate the existence of additional spatial dimensions in which all SM particles can propagate, leading to the existence of a series of excitations for each SM particle known as a Kaluza–Klein (KK) tower. This analysis considers the case of a single UED, with compactification radius $R \approx 1\ \mathrm{TeV}^{-1}$. The masses of the states of successive levels in the tower are separated by $\approx 1/R$; for a given KK level, the approximate mass degeneracy of the KK excitations is broken by radiative corrections [28]. The lightest KK particle (LKP) is the KK photon of the first level, denoted γ^*. At the LHC, the main UED process would be the production via the strong interaction of a pair of first-level KK quarks and/or gluons [29], which would decay via cascades involving other KK particles until reaching the LKP at the end of the decay chain. If the UED model is embedded in a larger space with N additional eV^{-1}-sized dimensions accessible only to gravity [30], the LKP could decay gravitationally via $\gamma^* \to \gamma + G$ [5, 6], where G represents one of a tower of eV-spaced graviton states, leading to a distribution of graviton mass between 0 and $1/R$. With two decay chains per event, the final state would again be $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}} + X$, where $E_{\mathrm{T}}^{\mathrm{miss}}$ results from the escaping gravitons and X represents SM particles emitted in the cascade decays.

The UED model considered here is defined by specifying R and Λ, the ultraviolet cut-off used in the calculation of radiative corrections to the KK masses. This analysis sets Λ such that $\Lambda R = 20$ [28]. For $1/R = 700$ GeV, the masses of the first-level KK photon, quark and gluon are 700, 815 and 865 GeV, respectively [31]. The γ^* mass is insensitive to Λ, while other KK masses typically change by a few percent when varying ΛR in the range 10–30. The gravitational decay widths of the KK particles are set by N and M_D, the Planck scale in the $(4+N)$-dimensional theory. For the chosen values of $N = 6$ and $M_D = 5$ TeV, and provided $1/R \lesssim 1$ TeV, the LKP is the only KK particle to have an appreciable rate of gravitational decay. The same parameter values were used in prior searches by D0 and ATLAS. D0 excluded values of $1/R < 477$ GeV at 95% CL [24]. ATLAS analysed 3.1 pb^{-1} of pp collisions data at $\sqrt{s} = 7$ TeV, excluding values of $1/R < 729$ GeV at 95% CL [1].

4 Simulated samples

For the GGM model, the full mass spectrum and the gluino branching ratios and decay widths were calculated for a range of gluino and neutralino masses using `SUSPECT` 2.41 [32] and `SDECAY` 1.3 [33]. The SUSY Les Houches Accord files for the model used may be found online [34]. The Monte Carlo (MC) signal samples were produced using `PYTHIA` 6.423 [35] with `MRST2007 LO`* [36] parton distribution functions (PDF). Cross sections were calculated at next-to-leading order (NLO) using `PROSPINO` 2.1 [37]. In the case of the UED model, a range of $1/R$ values was generated using the leading-order (LO) implementation of the UED model in `PYTHIA` [31]; no NLO calculations of UED processes are currently available. For both sets of samples, the MC10 parameter tune [38] was used. All signal and SM background samples were passed through a `GEANT4`-based simulation [39] of the ATLAS detector [40] including the simulation of pileup (multiple pp collisions within the same bunch crossing) of approximately 2 events per bunch crossing, similar to that seen in the data. The MC samples were reconstructed with the same algorithms that were used for the data.

5 ATLAS detector

The ATLAS detector [41] is a multi-purpose apparatus with a forward-backward symmetric cylindrical geometry and nearly 4π solid angle coverage. Closest to the beamline are tracking detectors that use layers of silicon-based ($|\eta| < 2.5$) and straw-tube ($|\eta| < 2.0$) detectors,[1] located inside a

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-

thin superconducting solenoid that provides a 2 T magnetic field, to measure the trajectories of charged particles. The solenoid is surrounded by a hermetic calorimeter system. A lead liquid-argon (LAr) sampling calorimeter is divided into a central barrel calorimeter and two end-cap calorimeters, each housed in a separate cryostat. Fine-granularity LAr electromagnetic (EM) calorimeters provide coverage for $|\eta| < 3.2$ to precisely measure the energy and position of electrons and photons. In the region $|\eta| < 2.5$, the EM calorimeters are segmented into three longitudinal layers. The second layer, in which most of the EM shower energy is deposited, is divided into cells of granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, with the first layer segmented with finer granularity [41] to provide rejection of neutral mesons in jets when selecting isolated photons. A presampler, covering $|\eta| < 1.8$, is used to correct for energy lost upstream of the calorimeter. An iron-scintillator tile calorimeter provides hadronic coverage in the range $|\eta| < 1.7$. In the end-caps ($|\eta| > 1.5$), LAr hadronic calorimeters match the outer $|\eta|$ limits of the end-cap EM calorimeters. LAr forward calorimeters provide both EM and hadronic energy measurements, and extend the coverage to $|\eta| < 4.9$, which is required for reliable $E_{\mathrm{T}}^{\mathrm{miss}}$ measurements. An extensive muon spectrometer system that incorporates large superconducting toroidal magnets lies outside the calorimeter system.

6 Photon and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction

The reconstruction of photons is described in detail in [42]. To select photon candidates, EM calorimeter clusters were required to satisfy several quality criteria and lie outside problematic calorimeter regions. EM calorimeter clusters without any matching track were considered to be unconverted photons; clusters that have a track match were considered to be electrons; clusters matched to a conversion vertex were considered to be converted photons. A conversion vertex is either a vertex that has two electron-like tracks, as determined by transition radiation in the straw-tube tracker, and is consistent with a massless parent object, or one electron-like track that has no track hits in the pixel vertexing layer. Photon candidates were required to be within $|\eta| < 1.81$ and to be outside the transition region $1.37 < |\eta| < 1.52$ between the barrel and the end-cap calorimeters. The analysis used "loose" and "tight" photon selections [42], which include a limit on the fraction of the energy in the hadronic calorimeter as well as requirements that the transverse width of the shower, measured in the middle layer of the EM calorimeter, be consistent with the narrow width expected for an EM shower. The tight photon selection uses, in addition, shape information from the first sampling layer to distinguish between isolated photons and photons from the decay of neutral mesons. The tight selection is approximately 85% efficient for both unconverted and converted photons while rejecting most of the background from hadronic jets [43].

The reconstruction of $E_{\mathrm{T}}^{\mathrm{miss}}$ was based on topological calorimeter clusters [44] with $|\eta| < 4.5$. The cluster energy was calibrated to correct for the non-compensating calorimeter response, energy losses in dead material, and out-of-cluster energies. Rare events with large transverse energies that are unrelated to the collision, concentrated in a few cells, and due mainly to electronic discharges and noise, have been observed. Cuts were applied to eliminate such backgrounds, rejecting fewer than 0.3% of the selected events while having a negligible impact on the GGM and UED signal efficiencies.

7 Data analysis

The data sample was collected during stable beam periods of 7 TeV pp collisions at the LHC, and corresponds to an integrated luminosity of $(36 \pm 1)\ \mathrm{pb}^{-1}$. Selected events had to satisfy a trigger requiring either a single EM cluster with $E_{\mathrm{T}} > 14$ GeV during the first $0.5\ \mathrm{pb}^{-1}$ of pp collisions or two loose photon candidates with $E_{\mathrm{T}} > 15$ GeV thereafter. Furthermore, they had to contain at least one reconstructed primary vertex consistent with the average beam spot position and with at least five associated tracks. The trigger and vertex requirements are very close to 100% efficient for signal MC events.

Events were retained if they had at least two tight photon candidates, one with $E_{\mathrm{T}} > 30$ GeV and the other with $E_{\mathrm{T}} > 20$ GeV. In addition, a photon isolation cut was applied, whereby the E_{T} in a cone of radius 0.2 in the η–ϕ space around the centre of the cluster, excluding all the cells belonging to the cluster (in a region with a size corresponding to 5×7 cells in $\eta \times \phi$ in the second layer of the EM calorimeter), had to be less than 10% of the transverse energy of the cluster. This requirement has a signal efficiency greater than 93% while rejecting a significant portion of the background from multijet events.

The signal region was defined as $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV, chosen to maximise sensitivity to the GGM and UED signal final states.

A total of 762 $\gamma\gamma$ candidate events were observed passing all selection cuts except the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut. After the $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV cut, no candidate events survive in the data. The E_{T} of the leading photon for events in this sample is shown

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axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates (R, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

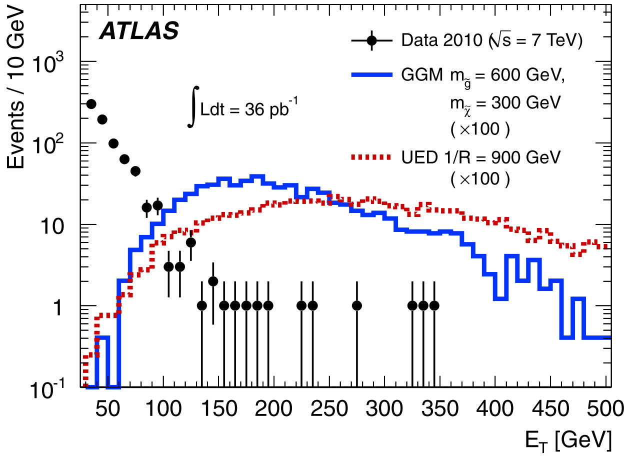

Fig. 1 The E_{T} spectrum of the leading photon in the $\gamma\gamma$ candidate events (points, statistical uncertainty only) together with the spectra from simulated GGM ($m_{\tilde{g}}/m_{\tilde{\chi}_1^0} = 600/300$ GeV) and UED ($1/R = 900$ GeV) samples, prior to the application of the $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV cut

in Fig. 1. Also shown is the E_{T} spectrum obtained from GGM MC samples for $m_{\tilde{g}} = 600$ GeV and $m_{\tilde{\chi}_1^0} = 300$ GeV and from UED MC samples for $1/R = 900$ GeV, representing model parameters near the expected exclusion limit.

8 Background estimation

Guided by the procedure developed in [24], the number of large $E_{\mathrm{T}}^{\mathrm{miss}}$ diphoton events from SM sources can be grouped into two primary components and estimated with dedicated control samples. The first of these components, referred to as QCD background, arises from a mixture of SM processes that include $\gamma\gamma$ production as well as γ + jet and multijet events with at least one jet misidentified as a photon. The second background component is due to $W + X$ and $t\bar{t}$ events, for which final-state neutrinos produce significant $E_{\mathrm{T}}^{\mathrm{miss}}$. These can pass the selection if an electron from the W or t-quark decay is misidentified as a photon and the second photon is either a real photon ($W\gamma$ events), a jet faking a photon (W + jets events), or a jet or second electron faking a photon ($t\bar{t}$ events).

In order to estimate the QCD background from γ + jet and multijet events, an independent "QCD$_\gamma$" control sample, designed to provide a model of the $E_{\mathrm{T}}^{\mathrm{miss}}$ response for events with jets faking photons, was defined by selecting events for which at least one of the photon candidates did not pass the tight photon identification. The background from QCD events producing two prompt photons was modeled using the $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum measured in a high-purity sample of $Z \to ee$ events, with no additional jets, selected by requiring two electrons [44] with $E_{\mathrm{T}} > 30$ GeV and $E_{\mathrm{T}} > 20$ GeV, respectively. Both electrons are required to have $|\eta| < 2.47$, excluding the transition region $1.37 < |\eta| < 1.52$. In addition, the dielectron invariant mass was required to be consistent with the Z mass. As confirmed by MC simulation, the $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum of the $Z \to ee$ sample with no additional jets, which is dominated by the calorimeter response to two genuine EM objects, accurately represents the $E_{\mathrm{T}}^{\mathrm{miss}}$ response of SM $\gamma\gamma$ events.

The QCD background is the dominant source of observed $\gamma\gamma$ events at low $E_{\mathrm{T}}^{\mathrm{miss}}$ and its spectrum, which contains a mixture of events with zero, one or two prompt photons, is expected to lie between the spectra from the QCD$_\gamma$ and $Z \to ee$ control samples. The $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum of the QCD$_\gamma$ control sample, which provides the best description of the $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum at low $E_{\mathrm{T}}^{\mathrm{miss}}$, was chosen to model the composite QCD background. The difference between this estimate and that derived from the $Z \to ee$ template was used to provide an estimate of the systematic uncertainty on the resulting background prediction. The QCD background was normalised to have the same number of events as the $\gamma\gamma$ candidate sample in the region $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV, where contributions from events with genuine $E_{\mathrm{T}}^{\mathrm{miss}}$, such as $W + X$ and $t\bar{t}$ events, can be neglected. It should be noted that a possible background contribution from $Z + X$ events, with the Z boson decaying to neutrinos, would be incorporated within this estimate of the QCD background, since it would enter the signal region through the misidentification of jets as photons.

The QCD$_\gamma$ template has one event with $E_{\mathrm{T}}^{\mathrm{miss}}$ greater than 125 GeV, whereas the $Z \to ee$ template has none. Taking into account the expected ratio of events in the portion of the control region with $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV to those in the signal region, this leads to a QCD background prediction of $0.034 \pm 0.034(\mathrm{stat}) \pm 0.034(\mathrm{syst})$ events. The QCD$_\gamma$ $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum is shown together with the $\gamma\gamma$ sample in Fig. 2.

The second significant background contribution, from $W + X$ and $t\bar{t}$ events, was estimated via an "electron–photon" control sample composed of events with both a photon and an electron with $E_{\mathrm{T}} > 20$ GeV, with the additional requirement that either the electron or photon has $E_{\mathrm{T}} > 30$ GeV, and scaled by the probability for an electron to be misidentified as a tight photon. This probability was estimated by comparing the rate at which photons and electrons pair with electrons to form an invariant mass consistent with that of the Z boson. The misidentification probability with the selection cuts used in this analysis varies between 5% and 12% as a function of η, since it depends on the amount of material in the inner detector. The $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum for this control sample is shown in Fig. 3, compared to the expected contributions from various background sources. The electron–photon control sample has a significant contribution from $Z \to ee$ events, for which one electron fakes a photon, and from QCD. Both of these contributions must be subtracted in order to predict the contribution to the $E_{\mathrm{T}}^{\mathrm{miss}}$

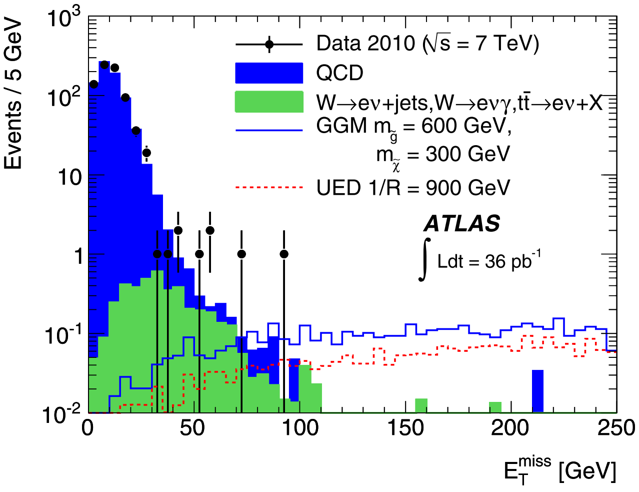

Fig. 2 $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra of the $\gamma\gamma$ candidates (points, statistical uncertainty only) and estimated background from the QCD (normalised to the number of $\gamma\gamma$ candidates with $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV) and $W(\to e\nu) + \text{jets}/\gamma$ and $t\bar{t}(\to e\nu) + \text{jets}$ sources, together with the spectra from simulated GGM ($m_{\tilde{g}}/m_{\tilde{\chi}_1^0} = 600/300$ GeV) and UED ($1/R = 900$ GeV) samples

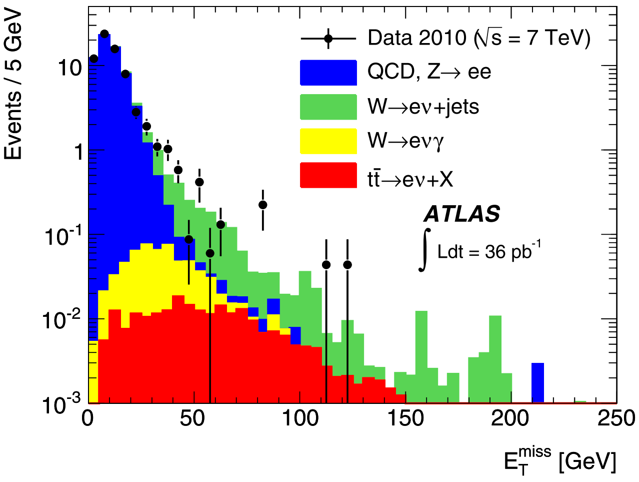

Fig. 3 $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum of the electron–photon control sample (points, statistical uncertainty only), normalised according to the probability for an electron to be misidentified as a tight photon, compared to the sum of the expected background, broken down by component (stacked histograms). For the purpose of this comparison, the expected contribution from $W(\to e\nu) + \text{jets}/\gamma$ and $t\bar{t}(\to e\nu) + \text{jets}$ events is taken directly from MC. At low values of $E_{\mathrm{T}}^{\mathrm{miss}}$, the spectrum is dominated by QCD events and $Z \to ee$ events for which one of the electrons has been misidentified as a photon. These two classes of events are accounted for (*blue* histogram) by scaling the QCD$_\gamma$ template to match the interval of the spectrum in the region $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV

distribution from events with genuine $E_{\mathrm{T}}^{\mathrm{miss}}$, such as $W + X$ and $t\bar{t}$ events. The contribution from QCD and $Z \to ee$ events was estimated by normalizing the QCD$_\gamma$ $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution to the scaled electron–photon $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the region $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV, as shown in Fig. 3. This distribution was then subtracted from the scaled electron–photon control sample, yielding a prediction for the contribution to the high-$E_{\mathrm{T}}^{\mathrm{miss}}$ diphoton sample from $W + X$ and $t\bar{t}$ events. For $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, the sample is dominated by events with genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ and electrons from $W \to e\nu$.

No events with $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV were observed in the electron–photon control sample; taking into account the measured electron-to-photon misidentification rate, this yields an upper limit on the background from $W + X$ and $t\bar{t}$ of 0.093 events at 90% CL. Two additional methods were employed to increase the statistical power of the electron–photon control sample. First, the photon selection requirement was loosened for the control sample, leading to an observation of one event in the signal region, and a corresponding background estimate of $0.027 \pm 0.027(\text{stat})$ events. Second, MC samples of the three main components ($W + \text{jets}$, $W + \gamma$ and $t\bar{t}$) were used to model the region where data is limited. The MC samples, which had the same electron and photon selection and scaling applied as for the electron–photon control sample, were normalised to the control sample, after the QCD and $Z \to ee$ subtraction, in the range $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV (to avoid the QCD and $Z \to ee$ dominated region at low $E_{\mathrm{T}}^{\mathrm{miss}}$). This MC extrapolation was used to determine the background with $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV, and led to an estimate of $0.057 \pm 0.015(\text{stat})$ background events. The estimate from the loosened-photon control sample provides a lower bound on the systematic uncertainty of this background component that lies 0.030 events below this central value. In addition, a Gaussian distribution with a mean of 0.057 and variance of 0.031 events has 90% of its probability density below 0.093 events, providing an upper bound of 0.031 events above the central value. Thus, a value of ± 0.031 events was chosen for the systematic uncertainty, yielding an estimate of $0.057 \pm 0.015(\text{stat}) \pm 0.031(\text{syst})$ for the background from $W + X$ and $t\bar{t}$ events. Also included in the quoted systematic uncertainty is the uncertainty ($\pm 10\%$) on the electron–photon fake rate and the uncertainty ($\pm 6\%$) on the subtraction of the QCD contribution to the scaled electron–photon control sample derived by replacing the QCD$_\gamma$ distribution with that of the $Z \to ee$ sample when performing the subtraction.

In addition to the QCD, $W + X$ and $t\bar{t}$ contributions, a small irreducible background contribution of 0.004 events from $W(\to e\nu)\gamma\gamma$ and $Z(\to \nu\nu)\gamma\gamma$ events was estimated directly from MC simulation. Backgrounds due to cosmic-ray and non-collision activity were suppressed through the use of timing and jet-quality cuts and by the primary vertex requirement, and are not expected to contribute significantly in the signal region.

Figure 2 shows the $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum of selected $\gamma\gamma$ candidates, superimposed on the total background prediction. Table 1 summarises the number of observed $\gamma\gamma$ candidates, as well as the expected backgrounds and two representative GGM and UED signal contributions, in several $E_{\mathrm{T}}^{\mathrm{miss}}$

Table 1 Numbers of observed $\gamma\gamma$ candidates, SM background candidates estimated from the QCD$_\gamma$ and electron–photon control samples and $W(\to e\nu) + \text{jets}/\gamma$ and $t\bar{t}(\to e\nu) + \text{jets}$ MC, and expected signal events from GGM with $(m_{\tilde{g}}/m_{\tilde{\chi}_1^0}) = (600/300)$ GeV and UED with $1/R = 900$ GeV, given in various $E_{\mathrm{T}}^{\mathrm{miss}}$ ranges. The uncertainties are statistical only. The *first row*, for $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV, is the control region used to normalise the QCD background to the number of observed $\gamma\gamma$ candidates. The total predicted background events also include the small contribution from $W(\to e\nu)\gamma\gamma$ and $Z(\to \nu\nu)\gamma\gamma$ events

$E_{\mathrm{T}}^{\mathrm{miss}}$ range	Data	Predicted background events			Expected signal events	
[GeV]	events	Total	QCD	$W/t\bar{t}(\to e\nu) + \text{jets}/\gamma$	GGM	UED
0–20	698	–	–	–	0.05 ± 0.01	0.02 ± 0.01
20–75	63	61.4 ± 2.3	58.3 ± 2.2	2.99 ± 0.12	0.59 ± 0.05	0.25 ± 0.02
75–125	1	0.38 ± 0.08	0.17 ± 0.08	0.19 ± 0.03	0.96 ± 0.06	0.43 ± 0.02
>125	0	0.10 ± 0.04	0.034 ± 0.034	0.057 ± 0.015	4.66 ± 0.14	5.35 ± 0.11

ranges. No indication of an excess at high $E_{\mathrm{T}}^{\mathrm{miss}}$ values, where UED and GGM are expected to dominate, is observed. No events are observed in the signal region $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV, compared to an expectation of $0.10 \pm 0.04(\text{stat}) \pm 0.05(\text{syst})$ background events.

9 Systematic uncertainties

The GGM signal efficiency was determined from MC over an area of GGM parameter space that ranges from 400 to 800 GeV for the gluino mass, and from 50 GeV to within 20 GeV of the gluino mass for the bino mass. The efficiency increases smoothly from 5% to 29% for $(m_{\tilde{g}}/m_{\tilde{\chi}_1^0}) = (400/50)$ GeV to (800/780) GeV; for low $m_{\tilde{\chi}_1^0}$, the bulk of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution lies below the cut of 125 GeV, leading to a less efficient selection. The UED signal efficiency, also determined from MC, increases smoothly from 37% for $1/R = 700$ GeV to 44% for $1/R = 1200$ GeV.

The various relative systematic uncertainties on the extraction of the GGM and UED signal cross sections are summarised in Table 2 for the example GGM and UED samples, including the 3.4% uncertainty on the integrated luminosity [45, 46] and the 0.7% uncertainty on the trigger requirement. Some sources of systematic uncertainty depend on kinematic properties and are expected to differ between GGM and UED. The resulting ranges provided in the following are ordered from low to high in the associated scales, i.e. $m_{\tilde{g}}$, $m_{\tilde{\chi}_1^0}$ and $1/R$ in the case of GGM and UED, respectively.

Table 2 Relative systematic uncertainties on the expected signal yield for GGM with $(m_{\tilde{g}}/m_{\tilde{\chi}_1^0}) = (600/300)$ GeV and UED with $1/R = 900$ GeV. No PDF and scale uncertainties are give for the UED case as the cross section is evaluated only to LO. More detail is provided in the text

<table>
<tr><th>Source of uncertainty</th><th colspan="2">Uncertainty</th></tr>
<tr><th></th><th>GGM</th><th>UED</th></tr>
<tr><td>Integrated luminosity</td><td colspan="2">3.4%</td></tr>
<tr><td>Trigger</td><td colspan="2">0.7%</td></tr>
<tr><td>Photon identification</td><td colspan="2">3.6%</td></tr>
<tr><td>Photon isolation</td><td>3.4%</td><td>1.5%</td></tr>
<tr><td>Effect of pileup</td><td colspan="2">1.0%</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and scale</td><td>3.7%</td><td>1.1%</td></tr>
<tr><td>Signal MC statistics</td><td>2.6%</td><td>1.2%</td></tr>
<tr><td>Total signal uncertainty</td><td>7.6%</td><td>5.4%</td></tr>
<tr><td>PDF and scale</td><td>25%</td><td>–</td></tr>
<tr><td>Total</td><td>26%</td><td>5.4%</td></tr>
</table>

Uncertainties on the efficiency for reconstructing and identifying the $\gamma\gamma$ pair arise from uncertainties on the impact of photon quality and isolation cuts, the scale of the photon E_{T} cut, the detailed material composition of the detector and from limitations in the MC description of the photon identification variables. The photon selection efficiency in the MC was tuned to match the efficiency observed in data by shifting the means of the discriminating variables used in the photon selection, such as the shower widths. The resulting estimate of the photon identification efficiency, tuned in this way, was within 5% of that of the un-tuned MC for all values of E_{T} and η. A systematic uncertainty was assigned to the tuning according to the uncertainty on the background contamination in the data sample, as well as by replacing the data with a MC sample generated with the inactive material in the region between the interaction point and calorimeter surface increased in a manner that reflects the uncertainty on the actual material distribution. An additional systematic uncertainty on the overall photon selection arises from the uncertainty on the overall amount of material in front of the calorimeter, and has been estimated using the same MC sample. The systematic uncertainty associated with removing photons in problematic regions of the calorimeter was derived by comparing, in MC and data, the fraction of photons within a fiducial region surrounding areas of degraded detector response. Combined in quadrature, these sources yielded a systematic uncertainty of 3.6% for both GGM and UED.

The systematic uncertainty on the efficiency of the isolation requirement was estimated by comparing distributions of the isolation variable for identified photons, after subtracting the estimated contributions from jets mistakenly identified as photons, with distributions of the isolation variable for MC photons. This yielded an uncertainty between 8.3% and 0.5% (GGM) and of 1.5% (UED). The systematic uncertainty arising from the photon energy scale (known to better than 1.5%) was found to be negligible. The influence of pileup, evaluated by comparing MC samples with different pileup configurations, led to a systematic uncertainty of 1.0%. Systematic effects due to the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction, estimated by varying the cluster energies within established uncertainty ranges, and by varying the expected $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution between the measured performance and MC expectations, contributed an uncertainty of 10.9% to 0.8% (GGM) and 2.1% to 0.9% (UED) on the signal efficiency. Finally, an uncertainty between 3.8% and 1.1% was attributed to the limited statistics of the MC signal samples. Added in quadrature, the total systematic uncertainty on the signal yield varies between 15.1% and 5.6% (GGM) and 5.8% and 5.4% (UED).

In the case of GGM, the dominant theoretical uncertainties arise from the limited knowledge of the proton PDF and the appropriate factorisation and renormalisation scales. The PDF uncertainties in the GGM cross sections were evaluated by using the `CTEQ6.6M` PDF error sets [47] in the `PROSPINO` cross section calculation and are estimated to be between 12% and 25%. The factorisation and renormalisation scales in the NLO `PROSPINO` calculation were increased and decreased by a factor of two, leading to a systematic uncertainty between 16% and 19%. The total theoretical uncertainty for GGM ranges from 20% to 31%. In the case of UED, NLO calculations of the cross sections are not yet available, leading to arbitrarily large scale errors that artificially degrade the derived limit. Thus, the LO cross sections were used with no assignment of theoretical uncertainties, e.g. PDF or scale uncertainties. The UED results are presented in a way that allows limits to be derived for other assumptions about the size and uncertainty of the UED cross section (see Fig. 4).

10 Extraction of limits

Based on the observation of zero events with $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV and the expected background of $0.10 \pm 0.04(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ events, a 95% CL upper limit was set on the number of events from new physics in the signal region.

Frequentist limits were derived using a profile likelihood ratio $\Lambda(s)$ [48], with the likelihood function of the fit given by $L(n|s,b,\theta) = P_{\mathrm{S}} \times C_{\mathrm{Syst}}$; n represents the number of observed events in data, s the strength of the new physics signal under consideration, b the expected background contribution, and θ the systematic uncertainties. The P_{S} function is a Poisson probability distribution for the number of signal-region events and C_{Syst} represents the constraints on systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density. The one-sided exclusion p-values were obtained using the test statistic $\Lambda(s)$ distribution from pseudo-experiments, and the CL_s method was used to exclude possible contributions from the signal [49].

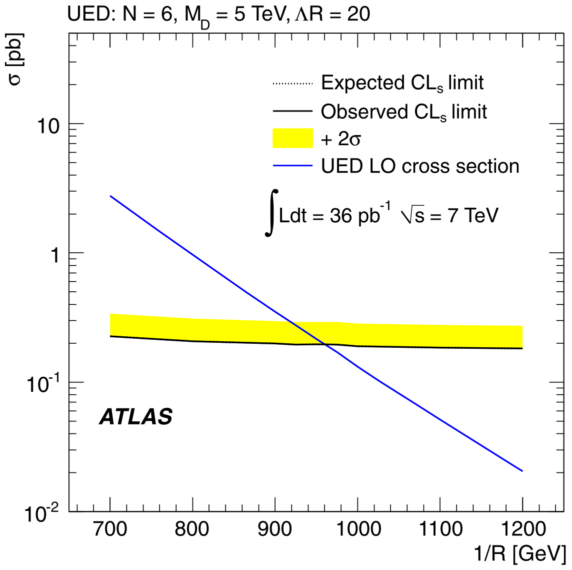

Fig. 4 Expected and observed 95% CL upper limits on the UED production cross section, and the LO theory cross section prediction, as a function of $1/R$. The observed limit, the $\pm 1\sigma$ expected error bands and the -2σ expected error band are degenerate with the expected limit. The UED model parameters are $N = 6$, $M_D = 5$ TeV and $\Lambda R = 20$

The number of events in the signal region from any scenario of physics beyond the SM (BSM) was found to be less than 3.0 at 95% CL. This number corresponds to 95% CL upper limits on production cross sections of $\sigma < 0.38$–0.65 pb in the GGM model ($m_{\tilde{\chi}_1^0} = 150$ GeV, $m_{\tilde{g}} = 400$–800 GeV) and $\sigma < 0.18$–0.23 pb in the UED model ($1/R = 700$–1200 GeV), shown as a function of $1/R$ for the case of the UED model in Fig. 4. These upper limits on cross section include systematic uncertainties on the background estimation, event selection and the luminosity.

These results can be interpreted in terms of 95% CL exclusion limits on specific parameters of the two new physics models considered. Figure 4 depicts the lower limit on the curvature parameter $1/R$ in the context of the UED model considered. The observed (expected) 95% CL exclusion region is $1/R < 961$ GeV ($1/R < 961$ GeV). Figure 5 shows the expected and observed lower limit on the GGM gluino mass as a function of the neutralino mass, with all other spar-

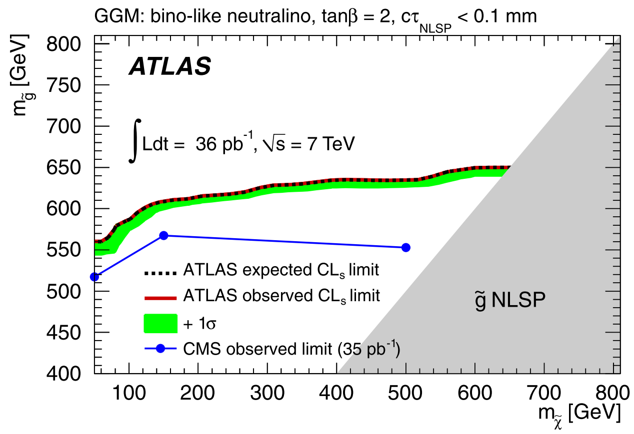

Fig. 5 Expected and observed 95% CL lower limits on the gluino mass as a function of the neutralino mass in the GGM model with a bino-like lightest neutralino as NLSP (the grey area indicates the region where the NLSP is the gluino, which was not considered here). The other sparticle masses are fixed to ∼1.5 TeV. Further model parameters are $\tan\beta = 2$ and $c\tau_{\mathrm{NLSP}} < 0.1$ mm. The observed limit and the -1σ expected error band are degenerate with the expected limit. CMS lower limits are from [26]

ticle masses, e.g. squarks, set to ∼1.5 TeV. In addition to the experimental systematic uncertainties, the limit also takes into account theoretical uncertainty on the production cross section. The limit depends only weakly on the neutralino mass, and a lower observed (expected) gluino mass limit of 560 GeV (560 GeV) is obtained for neutralino masses above 50 GeV. For comparison the lower limits from CMS [26] on the gluino mass for neutralino masses of 50, 175 and 500 GeV are shown in the same figure.

The limits presented here, obtained with all squark masses set to ∼1.5 TeV, are conservative, since values of other strongly charged sparticle (squark) masses that lie close to the excluded gluino mass increase the cross section for pair production of coloured SUSY particles, leading to a more stringent bounds on the gluino mass. The impact of variations in the systematic uncertainty is small: the observed limits change by less than 2 GeV if the magnitude of the systematic uncertainty is allowed to approach 0.

11 Conclusions

A search for $\gamma\gamma$ events with large $E_{\mathrm{T}}^{\mathrm{miss}}$, conducted using a 36 pb^{-1} sample of 7 TeV pp collision data recorded with the ATLAS detector at the LHC, found no evidence of an excess above the SM expectation: zero events were observed with an expected background of $0.10 \pm 0.04(\mathrm{stat}) \pm 0.05(\mathrm{syst})$. The results were used to set a model-independent 95% CL upper limit of 3.0 events on the observed number of diphoton events from new physics in the region $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV. 95% CL upper limits were also set on the production cross section for two particular models of new physics: $\sigma < 0.38$–0.65 pb for the GGM model ($m_{\tilde{\chi}_1^0} = 150$ GeV) and $\sigma < 0.18$–0.23 pb for the UED model. These limits are interpreted in terms of constraints on parameters of specific new physics models. Under the GGM hypothesis, a lower limit on the gluino mass of 560 GeV is determined for bino masses above 50 GeV, while a lower limit of $1/R > 961$ GeV is set on the UED compactification radius R. These limits provide the most stringent tests of these models to date.

Acknowledgements We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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The ATLAS Collaboration

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Buttar[53], J.M. Butterworth[77], W. Buttinger[27], T. Byatt[77], S. Cabrera Urbán[167], D. Caforio[19a,19b], O. Cakir[3a], P. Calafiura[14], G. Calderini[78], P. Calfayan[98], R. Calkins[106], L.P. Caloba[23a], R. Caloi[132a,132b], D. Calvet[33], S. Calvet[33], R. Camacho Toro[33], P. Camarri[133a,133b], M. Cambiaghi[119a,119b], D. Cameron[117], S. Campana[29], M. Campanelli[77], V. Canale[102a,102b], F. Canelli[30], A. Canepa[159a], J. Cantero[80], L. Capasso[102a,102b], M.D.M. Capeans Garrido[29], I. Caprini[25a], M. Caprini[25a], D. Capriotti[99], M. Capua[36a,36b], R. Caputo[148], C. Caramarcu[25a], R. Cardarelli[133a], T. Carli[29], G. Carlino[102a], L. Carminati[89a,89b], B. Caron[159a], S. Caron[48], G.D. Carrillo Montoya[172], A.A. Carter[75], J.R. Carter[27], J. Carvalho[124a,h], D. Casadei[108], M.P. Casado[11], M. Cascella[122a,122b], C. Caso[50a,50b,*], A.M. Castaneda Hernandez[172], E. Castaneda-Miranda[172], V. Castillo Gimenez[167], N.F. Castro[124a], G. Cataldi[72a], F. Cataneo[29], A. Catinaccio[29], J.R. Catmore[71], A. Cattai[29], G. Cattani[133a,133b], S. Caughron[88], D. Cauz[164a,164c], P. Cavalleri[78], D. Cavalli[89a], M. Cavalli-Sforza[11], V. Cavasinni[122a,122b], F. Ceradini[134a,134b], A.S. Cerqueira[23a], A. Cerri[29], L. Cerrito[75], F. Cerutti[47], S.A. Cetin[18b], F. Cevenini[102a,102b], A. Chafaq[135a], D. Chakraborty[106], K. Chan[2], B. Chapleau[85], J.D. Chapman[27], J.W. Chapman[87], E. Chareyre[78], D.G. Charlton[17], V. Chavda[82], C.A. Chavez Barajas[29], S. Cheatham[85], S. Chekanov[5], S.V. Chekulaev[159a], G.A. Chelkov[65], M.A. Chelstowska[104], C. Chen[64], H. Chen[24], S. Chen[32c], T. Chen[32c], X. Chen[172], S. Cheng[32a], A. Cheplakov[65], V.F. Chepurnov[65], R. Cherkaoui El Moursli[135e], V. Chernyatin[24], E. Cheu[6], S.L. Cheung[158], L. Chevalier[136], G. Chiefari[102a,102b], L. Chikovani[51], J.T. Childers[58a], A. Chilingarov[71], G. Chiodini[72a], M.V. Chizhov[65], G. Choudalakis[30], S. Chouridou[137], I.A. Christidi[77], A. Christov[48], D. Chromek-Burckhart[29], M.L. Chu[151], J. Chudoba[125], G. Ciapetti[132a,132b],

K. Ciba[37], A.K. Ciftci[3a], R. Ciftci[3a], D. Cinca[33], V. Cindro[74], M.D. Ciobotaru[163], C. Ciocca[19a,19b], A. Ciocio[14], M. Cirilli[87], M. Ciubancan[25a], A. Clark[49], P.J. Clark[45], W. Cleland[123], J.C. Clemens[83], B. Clement[55], C. Clement[146a,146b], R.W. Clifft[129], Y. Coadou[83], M. Cobal[164a,164c], A. Coccaro[50a,50b], J. Cochran[64], P. Coe[118], J.G. Cogan[143], J. Coggeshall[165], E. Cogneras[177], C.D. Cojocaru[28], J. Colas[4], A.P. Colijn[105], C. Collard[115], N.J. Collins[17], C. Collins-Tooth[53], J. Collot[55], G. Colon[84], P. Conde Muiño[124a], E. Coniavitis[118], M.C. Conidi[11], M. Consonni[104], V. Consorti[48], S. Constantinescu[25a], C. Conta[119a,119b], F. Conventi[102a,i], J. Cook[29], M. Cooke[14], B.D. Cooper[77], A.M. Cooper-Sarkar[118], N.J. Cooper-Smith[76], K. Copic[34], T. Cornelissen[50a,50b], M. Corradi[19a], F. Corriveau[85,j], A. Cortes-Gonzalez[165], G. Cortiana[99], G. Costa[89a], M.J. Costa[167], D. Costanzo[139], T. Costin[30], D. Côté[29], R. Coura Torres[23a], L. Courneyea[169], G. Cowan[76], C. Cowden[27], B.E. Cox[82], K. Cranmer[108], F. Crescioli[122a,122b], M. Cristinziani[20], G. Crosetti[36a,36b], R. Crupi[72a,72b], S. Crépé-Renaudin[55], C.-M. Cuciuc[25a], C. Cuenca Almenar[175], T. Cuhadar Donszelmann[139], S. Cuneo[50a,50b], M. Curatolo[47], C.J. Curtis[17], P. Cwetanski[61], H. Czirr[141], Z. Czyczula[117], S. D'Auria[53], M. D'Onofrio[73], A. D'Orazio[132a,132b], P.V.M. Da Silva[23a], C. Da Via[82], W. Dabrowski[37], T. Dai[87], C. Dallapiccola[84], M. Dam[35], M. Dameri[50a,50b], D.S. Damiani[137], H.O. Danielsson[29], D. Dannheim[99], V. Dao[49], G. Darbo[50a], G.L. Darlea[25b], C. Daum[105], J.P. Dauvergne[29], W. Davey[86], T. Davidek[126], N. Davidson[86], R. Davidson[71], E. Davies[118,c], M. Davies[93], A.R. Davison[77], Y. Davygora[58a], E. Dawe[142], I. Dawson[139], J.W. Dawson[5,*], R.K. Daya[39], K. De[7], R. de Asmundis[102a], S. De Castro[19a,19b], P.E. De Castro Faria Salgado[24], S. De Cecco[78], J. de Graat[98], N. De Groot[104], P. de Jong[105], C. De La Taille[115], H. De la Torre[80], B. De Lotto[164a,164c], L. De Mora[71], L. De Nooij[105], M. De Oliveira Branco[29], D. De Pedis[132a], P. de Saintignon[55], A. De Salvo[132a], U. De Sanctis[164a,164c], A. De Santo[149], J.B. De Vivie De Regie[115], S. Dean[77], D.V. Dedovich[65], J. Degenhardt[120], M. Dehchar[118], M. Deile[98], C. Del Papa[164a,164c], J. Del Peso[80], T. Del Prete[122a,122b], M. Deliyergiyev[74], A. Dell'Acqua[29], L. Dell'Asta[89a,89b], M. Della Pietra[102a,i], D. della Volpe[102a,102b], M. Delmastro[29], P. Delpierre[83], N. Delruelle[29], P.A. Delsart[55], C. Deluca[148], S. Demers[175], M. Demichev[65], B. Demirkoz[11,k], J. Deng[163], S.P. Denisov[128], D. Derendarz[38], J.E. Derkaoui[135d], F. Derue[78], P. Dervan[73], K. Desch[20], E. Devetak[148], P.O. Deviveiros[158], A. Dewhurst[129], B. DeWilde[148], S. Dhaliwal[158], R. Dhullipudi[24,l], A. Di Ciaccio[133a,133b], L. Di Ciaccio[4], A. Di Girolamo[29], B. Di Girolamo[29], S. Di Luise[134a,134b], A. Di Mattia[88], B. Di Micco[29], R. Di Nardo[133a,133b], A. Di Simone[133a,133b], R. Di Sipio[19a,19b], M.A. Diaz[31a], F. Diblen[18c], E.B. Diehl[87], J. Dietrich[41], T.A. Dietzsch[58a], S. Diglio[115], K. Dindar Yagci[39], J. Dingfelder[20], C. Dionisi[132a,132b], P. Dita[25a], S. Dita[25a], F. Dittus[29], F. Djama[83], T. Djobava[51], M.A.B. do Vale[23a], A. Do Valle Wemans[124a], T.K.O. Doan[4], M. Dobbs[85], R. Dobinson[29,*], D. Dobos[42], E. Dobson[29], M. Dobson[163], J. Dodd[34], C. Doglioni[118], T. Doherty[53], Y. Doi[66,*], J. Dolejsi[126], I. Dolenc[74], Z. Dolezal[126], B.A. Dolgoshein[96,*], T. Dohmae[155], M. Donadelli[23b], M. Donega[120], J. Donini[55], J. Dopke[29], A. Doria[102a], A. Dos Anjos[172], M. Dosil[11], A. Dotti[122a,122b], M.T. Dova[70], J.D. Dowell[17], A.D. Doxiadis[105], A.T. Doyle[53], Z. Drasal[126], J. Drees[174], N. Dressnandt[120], H. Drevermann[29], C. Driouichi[35], M. Dris[9], J. Dubbert[99], T. Dubbs[137], S. Dube[14], E. Duchovni[171], G. Duckeck[98], A. Dudarev[29], F. Dudziak[64], M. Dührssen[29], I.P. Duerdoth[82], L. Duflot[115], M.-A. Dufour[85], M. Dunford[29], H. Duran Yildiz[3b], R. Duxfield[139], M. Dwuznik[37], F. Dydak[29], D. Dzahini[55], M. Düren[52], W.L. Ebenstein[44], J. Ebke[98], S. Eckert[48], S. Eckweiler[81], K. Edmonds[81], C.A. Edwards[76], N.C. Edwards[53], W. Ehrenfeld[41], T. Ehrich[99], T. Eifert[29], G. Eigen[13], K. Einsweiler[14], E. Eisenhandler[75], T. Ekelof[166], M. El Kacimi[135c], M. Ellert[166], S. Elles[4], F. Ellinghaus[81], K. Ellis[75], N. Ellis[29], J. Elmsheuser[98], M. Elsing[29], R. Ely[14], D. Emeliyanov[129], R. Engelmann[148], A. Engl[98], B. Epp[62], A. Eppig[87], J. Erdmann[54], A. Ereditato[16], D. Eriksson[146a], J. Ernst[1], M. Ernst[24], J. Ernwein[136], D. Errede[165], S. Errede[165], E. Ertel[81], M. Escalier[115], C. Escobar[167], X. Espinal Curull[11], B. Esposito[47], F. Etienne[83], A.I. Etienvre[136], E. Etzion[153], D. Evangelakou[54], H. Evans[61], L. Fabbri[19a,19b], C. Fabre[29], R.M. Fakhrutdinov[128], S. Falciano[132a], Y. Fang[172], M. Fanti[89a,89b], A. Farbin[7], A. Farilla[134a], J. Farley[148], T. Farooque[158], S.M. Farrington[118], P. Farthouat[29], P. Fassnacht[29], D. Fassouliotis[8], B. Fatholahzadeh[158], A. Favareto[89a,89b], L. Fayard[115], S. Fazio[36a,36b], R. Febbraro[33], P. Federic[144a], O.L. Fedin[121], W. Fedorko[88], M. Fehling-Kaschek[48], L. Feligioni[83], D. Fellmann[5], C.U. Felzmann[86], C. Feng[32d], E.J. Feng[30], A.B. Fenyuk[128], J. Ferencei[144b], J. Ferland[93], W. Fernando[109], S. Ferrag[53], J. Ferrando[53], V. Ferrara[41], A. Ferrari[166], P. Ferrari[105], R. Ferrari[119a], A. Ferrer[167], M.L. Ferrer[47], D. Ferrere[49], C. Ferretti[87], A. Ferretto Parodi[50a,50b], M. Fiascaris[30], F. Fiedler[81], A. Filipčič[74], A. Filippas[9], F. Filthaut[104], M. Fincke-Keeler[169], M.C.N. Fiolhais[124a,h], L. Fiorini[167], A. Firan[39], G. Fischer[41], P. Fischer[20], M.J. Fisher[109], S.M. Fisher[129], M. Flechl[48], I. Fleck[141], J. Fleckner[81], P. Fleischmann[173], S. Fleischmann[174], T. Flick[174], L.R. Flores Castillo[172], M.J. Flowerdew[99], F. Föhlisch[58a], M. Fokitis[9], T. Fonseca Martin[16], D.A. Forbush[138], A. Formica[136], A. Forti[82], D. Fortin[159a], J.M. Foster[82], D. Fournier[115], A. Foussat[29], A.J. Fowler[44], K. Fowler[137], H. Fox[71], P. Francavilla[122a,122b], S. Franchino[119a,119b], D. Francis[29], T. Frank[171], M. Franklin[57], S. Franz[29], M. Fraternali[119a,119b], S. Fratina[120], S.T. French[27], R. Froeschl[29], D. Froidevaux[29], J.A. Frost[27], C. Fukunaga[156], E. Fullana Torregrosa[29], J. Fuster[167], C. Gabaldon[29], O. Gabizon[171], T. Gadfort[24], S. Gadomski[49], G. Gagliardi[50a,50b], P. Gagnon[61], C. Galea[98], E.J. Gallas[118], M.V. Gallas[29], V. Gallo[16], B.J. Gallop[129], P. Gallus[125], E. Galyaev[40], K.K. Gan[109], Y.S. Gao[143,f], V.A. Gapienko[128], A. Gaponenko[14], F. Garberson[175], M. Garcia-Sciveres[14], C. García[167], J.E. García Navarro[49], R.W. Gardner[30], N. Garelli[29], H. Garitaonandia[105], V. Garonne[29],

J. Garvey[17], C. Gatti[47], G. Gaudio[119a], O. Gaumer[49], B. Gaur[141], L. Gauthier[136], I.L. Gavrilenko[94], C. Gay[168], G. Gaycken[20], J.-C. Gayde[29], E.N. Gazis[9], P. Ge[32d], C.N.P. Gee[129], D.A.A. Geerts[105], Ch. Geich-Gimbel[20], K. Gellerstedt[146a,146b], C. Gemme[50a], A. Gemmell[53], M.H. Genest[98], S. Gentile[132a,132b], M. George[54], S. George[76], P. Gerlach[174], A. Gershon[153], C. Geweniger[58a], H. Ghazlane[135b], P. Ghez[4], N. Ghodbane[33], B. Giacobbe[19a], S. Giagu[132a,132b], V. Giakoumopoulou[8], V. Giangiobbe[122a,122b], F. Gianotti[29], B. Gibbard[24], A. Gibson[158], S.M. Gibson[29], L.M. Gilbert[118], M. Gilchriese[14], V. Gilewsky[91], D. Gillberg[28], A.R. Gillman[129], D.M. Gingrich[2,e], J. Ginzburg[153], N. Giokaris[8], R. Giordano[102a,102b], F.M. Giorgi[15], P. Giovannini[99], P.F. Giraud[136], D. Giugni[89a], M. Giunta[132a,132b], P. Giusti[19a], B.K. Gjelsten[117], L.K. Gladilin[97], C. Glasman[80], J. Glatzer[48], A. Glazov[41], K.W. Glitza[174], G.L. Glonti[65], J. Godfrey[142], J. Godlewski[29], M. Goebel[41], T. Göpfert[43], C. Goeringer[81], C. Gössling[42], T. Göttfert[99], S. Goldfarb[87], D. Goldin[39], T. Golling[175], S.N. Golovnia[128], A. Gomes[124a,b], L.S. Gomez Fajardo[41], R. Gonçalo[76], J. Goncalves Pinto Firmino Da Costa[41], L. Gonella[20], A. Gonidec[29], S. Gonzalez[172], S. González de la Hoz[167], M.L. Gonzalez Silva[26], S. Gonzalez-Sevilla[49], J.J. Goodson[148], L. Goossens[29], P.A. Gorbounov[95], H.A. Gordon[24], I. Gorelov[103], G. Gorfine[174], B. Gorini[29], E. Gorini[72a,72b], A. Gorišek[74], E. Gornicki[38], S.A. Gorokhov[128], V.N. Goryachev[128], B. Gosdzik[41], M. Gosselink[105], M.I. Gostkin[65], M. Gouanère[4], I. Gough Eschrich[163], M. Gouighri[135a], D. Goujdami[135c], M.P. Goulette[49], A.G. Goussiou[138], C. Goy[4], I. Grabowska-Bold[163,g], V. Grabski[176], P. Grafström[29], C. Grah[174], K.-J. Grahn[41], F. Grancagnolo[72a], S. Grancagnolo[15], V. Grassi[148], V. Gratchev[121], N. Grau[34], H.M. Gray[29], J.A. Gray[148], E. Graziani[134a], O.G. Grebenyuk[121], D. Greenfield[129], T. Greenshaw[73], Z.D. Greenwood[24,l], I.M. Gregor[41], P. Grenier[143], J. Griffiths[138], N. Grigalashvili[65], A.A. Grillo[137], S. Grinstein[11], Y.V. Grishkevich[97], J.-F. Grivaz[115], J. Grognuz[29], M. Groh[99], E. Gross[171], J. Grosse-Knetter[54], J. Groth-Jensen[171], K. Grybel[141], V.J. Guarino[5], D. Guest[175], C. Guicheney[33], A. Guida[72a,72b], T. Guillemin[4], S. Guindon[54], H. Guler[85,m], J. Gunther[125], B. Guo[158], J. Guo[34], A. Gupta[30], Y. Gusakov[65], V.N. Gushchin[128], A. Gutierrez[93], P. Gutierrez[111], N. Guttman[153], O. Gutzwiller[172], C. Guyot[136], C. Gwenlan[118], C.B. Gwilliam[73], A. Haas[143], S. Haas[29], C. Haber[14], R. Hackenburg[24], H.K. Hadavand[39], D.R. Hadley[17], P. Haefner[99], F. Hahn[29], S. Haider[29], Z. Hajduk[38], H. Hakobyan[176], J. Haller[54], K. Hamacher[174], P. Hamal[113], A. Hamilton[49], S. Hamilton[161], H. Han[32a], L. Han[32b], K. Hanagaki[116], M. Hance[120], C. Handel[81], P. Hanke[58a], J.R. Hansen[35], J.B. Hansen[35], J.D. Hansen[35], P.H. Hansen[35], P. Hansson[143], K. Hara[160], G.A. Hare[137], T. Harenberg[174], S. Harkusha[90], D. Harper[87], R.D. Harrington[21], O.M. Harris[138], K. Harrison[17], J. Hartert[48], F. Hartjes[105], T. Haruyama[66], A. Harvey[56], S. Hasegawa[101], Y. Hasegawa[140], S. Hassani[136], M. Hatch[29], D. Hauff[99], S. Haug[16], M. Hauschild[29], R. Hauser[88], M. Havranek[20], B.M. Hawes[118], C.M. Hawkes[17], R.J. Hawkings[29], D. Hawkins[163], T. Hayakawa[67], D. Hayden[76], H.S. Hayward[73], S.J. Haywood[129], E. Hazen[21], M. He[32d], S.J. Head[17], V. Hedberg[79], L. Heelan[7], S. Heim[88], B. Heinemann[14], S. Heisterkamp[35], L. Helary[4], M. Heller[115], S. Hellman[146a,146b], D. Hellmich[20], C. Helsens[11], R.C.W. Henderson[71], M. Henke[58a], A. Henrichs[54], A.M. Henriques Correia[29], S. Henrot-Versille[115], F. Henry-Couannier[83], C. Hensel[54], T. Henß[174], C.M. Hernandez[7], Y. Hernández Jiménez[167], R. Herrberg[15], A.D. Hershenhorn[152], G. Herten[48], R. Hertenberger[98], L. Hervas[29], N.P. Hessey[105], A. Hidvegi[146a], E. Higón-Rodriguez[167], D. Hill[5,*], J.C. Hill[27], N. Hill[5], K.H. Hiller[41], S. Hillert[20], S.J. Hillier[17], I. Hinchliffe[14], E. Hines[120], M. Hirose[116], F. Hirsch[42], D. Hirschbuehl[174], J. Hobbs[148], N. Hod[153], M.C. Hodgkinson[139], P. Hodgson[139], A. Hoecker[29], M.R. Hoeferkamp[103], J. Hoffman[39], D. Hoffmann[83], M. Hohlfeld[81], M. Holder[141], A. Holmes[118], S.O. Holmgren[146a], T. Holy[127], J.L. Holzbauer[88], Y. Homma[67], T.M. Hong[120], L. Hooft van Huysduynen[108], T. Horazdovsky[127], C. Horn[143], S. Horner[48], K. Horton[118], J.-Y. Hostachy[55], S. Hou[151], M.A. Houlden[73], A. Hoummada[135a], J. Howarth[82], D.F. Howell[118], I. Hristova[41], J. Hrivnac[115], I. Hruska[125], T. Hryn'ova[4], P.J. Hsu[175], S.-C. Hsu[14], G.S. 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Kaplan[175], A. Kapliy[30], J. Kaplon[29], D. Kar[43], M. Karagoz[118], M. Karnevskiy[41], K. Karr[5], V. Kartvelishvili[71], A.N. Karyukhin[128], L. Kashif[172], A. Kasmi[39], R.D. Kass[109],

A. Kastanas[13], M. Kataoka[4], Y. Kataoka[155], E. Katsoufis[9], J. Katzy[41], V. Kaushik[6], K. Kawagoe[67], T. Kawamoto[155], G. Kawamura[81], M.S. Kayl[105], V.A. Kazanin[107], M.Y. Kazarinov[65], J.R. Keates[82], R. Keeler[169], R. Kehoe[39], M. Keil[54], G.D. Kekelidze[65], M. Kelly[82], J. Kennedy[98], C.J. Kenney[143], M. Kenyon[53], O. Kepka[125], N. Kerschen[29], B.P. Kerševan[74], S. Kersten[174], K. Kessoku[155], C. Ketterer[48], J. Keung[158], M. Khakzad[28], F. Khalil-zada[10], H. Khandanyan[165], A. Khanov[112], D. Kharchenko[65], A. Khodinov[96], A.G. Kholodenko[128], A. Khomich[58a], T.J. Khoo[27], G. Khoriauli[20], A. Khoroshilov[174], N. Khovanskiy[65], V. Khovanskiy[95], E. Khramov[65], J. Khubua[51], H. Kim[7], M.S. Kim[2], P.C. Kim[143], S.H. Kim[160], N. Kimura[170], O. Kind[15], B.T. King[73], M. King[67], R.S.B. King[118], J. Kirk[129], G.P. Kirsch[118], L.E. Kirsch[22], A.E. Kiryunin[99], D. Kisielewska[37], T. Kittelmann[123], A.M. Kiver[128], H. Kiyamura[67], E. Kladiva[144b], J. Klaiber-Lodewigs[42], M. Klein[73], U. Klein[73], K. Kleinknecht[81], M. Klemetti[85], A. Klier[171], A. Klimentov[24], R. Klingenberg[42], E.B. Klinkby[35], T. Klioutchnikova[29], P.F. Klok[104], S. Klous[105], E.-E. Kluge[58a], T. Kluge[73], P. Kluit[105], S. Kluth[99], E. Kneringer[62], J. Knobloch[29], E.B.F.G. Knoops[83], A. Knue[54], B.R. Ko[44], T. Kobayashi[155], M. Kobel[43], M. Kocian[143], A. Kocnar[113], P. Kodys[126], K. Köneke[29], A.C. König[104], S. Koenig[81], L. Köpke[81], F. Koetsveld[104], P. Koevesarki[20], T. Koffas[29], E. Koffeman[105], F. Kohn[54], Z. Kohout[127], T. Kohriki[66], T. Koi[143], T. Kokott[20], G.M. Kolachev[107], H. Kolanoski[15], V. Kolesnikov[65], I. Koletsou[89a], J. Koll[88], D. Kollar[29], M. Kollefrath[48], S.D. Kolya[82], A.A. Komar[94], J.R. Komaragiri[142], Y. Komori[155], T. Kondo[66], T. Kono[41,o], A.I. Kononov[48], R. Konoplich[108,p], N. Konstantinidis[77], A. Kootz[174], S. Koperny[37], S.V. Kopikov[128], K. Korcyl[38], K. Kordas[154], V. Koreshev[128], A. Korn[14], A. Korol[107], I. Korolkov[11], E.V. Korolkova[139], V.A. Korotkov[128], O. Kortner[99], S. Kortner[99], V.V. Kostyukhin[20], M.J. Kotamäki[29], S. Kotov[99], V.M. Kotov[65], A. Kotwal[44], C. Kourkoumelis[8], V. Kouskoura[154], A. Koutsman[105], R. Kowalewski[169], T.Z. Kowalski[37], W. Kozanecki[136], A.S. Kozhin[128], V. Kral[127], V.A. Kramarenko[97], G. Kramberger[74], O. Krasel[42], M.W. Krasny[78], A. Krasznahorkay[108], J. Kraus[88], A. Kreisel[153], F. Krejci[127], J. Kretzschmar[73], N. Krieger[54], P. Krieger[158], K. Kroeninger[54], H. Kroha[99], J. Kroll[120], J. Kroseberg[20], J. Krstic[12a], U. Kruchonak[65], H. Krüger[20], T. Kruker[16], Z.V. Krumshteyn[65], A. Kruth[20], T. Kubota[86], S. Kuehn[48], A. Kugel[58c], T. Kuhl[174], D. Kuhn[62], V. Kukhtin[65], Y. Kulchitsky[90], S. Kuleshov[31b], C. Kummer[98], M. Kuna[78], N. Kundu[118], J. Kunkle[120], A. Kupco[125], H. Kurashige[67], M. 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Lee[105], J.S.H. Lee[150], S.C. Lee[151], L. Lee[175], M. Lefebvre[169], M. Legendre[136], A. Leger[49], B.C. LeGeyt[120], F. Legger[98], C. Leggett[14], M. Lehmacher[20], G. Lehmann Miotto[29], X. Lei[6], M.A.L. Leite[23b], R. Leitner[126], D. Lellouch[171], J. Lellouch[78], M. Leltchouk[34], V. Lendermann[58a], K.J.C. Leney[145b], T. Lenz[174], G. Lenzen[174], B. Lenzi[29], K. Leonhardt[43], S. Leontsinis[9], C. Leroy[93], J.-R. Lessard[169], J. Lesser[146a], C.G. Lester[27], A. Leung Fook Cheong[172], J. Levêque[4], D. Levin[87], L.J. Levinson[171], M.S. Levitski[128], M. Lewandowska[21], A. Lewis[118], G.H. Lewis[108], A.M. Leyko[20], M. Leyton[15], B. Li[83], H. Li[172], S. Li[32b,d], X. Li[87], Z. Liang[39], Z. Liang[118,q], B. Liberti[133a], P. Lichard[29], M. Lichtnecker[98], K. Lie[165], W. Liebig[13], R. Lifshitz[152], J.N. Lilley[17], C. Limbach[20], A. Limosani[86], M. Limper[63], S.C. Lin[151,r], F. Linde[105], J.T. Linnemann[88], E. Lipeles[120], L. Lipinsky[125], A. Lipniacka[13], T.M. Liss[165], D. Lissauer[24], A. Lister[49], A.M. Litke[137], C. Liu[28], D. Liu[151,s], H. Liu[87], J.B. Liu[87], M. Liu[32b], S. Liu[2], Y. Liu[32b], M. Livan[119a,119b], S.S.A. Livermore[118], A. Lleres[55], J. Llorente Merino[80], S.L. Lloyd[75], E. Lobodzinska[41], P. Loch[6], W.S. Lockman[137], S. Lockwitz[175], T. Loddenkoetter[20], F.K. Loebinger[82], A. Loginov[175], C.W. Loh[168], T. Lohse[15], K. Lohwasser[48], M. Lokajicek[125], J. Loken[118], V.P. Lombardo[4], R.E. Long[71], L. Lopes[124a,b], D. Lopez Mateos[34,t], M. Losada[162], P. Loscutoff[14], F. Lo Sterzo[132a,132b], M.J. Losty[159a], X. Lou[40], A. Lounis[115], K.F. Loureiro[162], J. Love[21], P.A. Love[71], A.J. Lowe[143,f], F. Lu[32a], H.J. Lubatti[138], C. Luci[132a,132b], A. Lucotte[55], A. Ludwig[43], D. Ludwig[41], I. Ludwig[48], J. Ludwig[48], F. Luehring[61], G. Luijckx[105], D. Lumb[48], L. Luminari[132a], E. Lund[117], B. Lund-Jensen[147], B. Lundberg[79], J. Lundberg[146a,146b], J. Lundquist[35], M. Lungwitz[81], A. Lupi[122a,122b], G. Lutz[99], D. Lynn[24], J. Lys[14], E. Lytken[79], H. Ma[24], L.L. Ma[172], J.A. Macana Goia[93], G. Maccarrone[47], A. Macchiolo[99], B. Maček[74], J. Machado Miguens[124a], D. Macina[49], R. Mackeprang[35], R.J. Madaras[14], W.F. Mader[43], R. Maenner[58c], T. Maeno[24], P. Mättig[174], S. Mättig[41], P.J. Magalhaes Martins[124a,h], L. Magnoni[29], E. Magradze[54], Y. Mahalalel[153], K. Mahboubi[48], G. Mahout[17], C. Maiani[132a,132b], C. Maidantchik[23a], A. Maio[124a,b], S. Majewski[24], Y. Makida[66], N. Makovec[115], P. Mal[6], Pa. Malecki[38], P. Malecki[38], V.P. Maleev[121], F. Malek[55], U. Mallik[63], D. Malon[5], S. Maltezos[9], V. Malyshev[107], S. Malyukov[29], R. Mameghani[98], J. Mamuzic[12b], A. Manabe[66], L. Mandelli[89a], I. Mandić[74], R. Mandrysch[15], J. Maneira[124a], P.S. Mangeard[88], I.D. Manjavidze[65], A. Mann[54], P.M. Manning[137], A. Manousakis-Katsikakis[8], B. Mansoulie[136], A. Manz[99], A. Mapelli[29], L. Mapelli[29], L. March[80], J.F. Marchand[29], F. Marchese[133a,133b], G. Marchiori[78], M. Marcisovsky[125], A. Marin[21,*], C.P. Marino[61], F. Marroquim[23a],

R. Marshall[82], Z. Marshall[29], F.K. Martens[158], S. Marti-Garcia[167], A.J. Martin[175], B. Martin[29], B. Martin[88], F.F. Martin[120], J.P. Martin[93], Ph. Martin[55], T.A. Martin[17], B. Martin dit Latour[49], M. Martinez[11], V. Martinez Outschoorn[57], A.C. Martyniuk[82], M. Marx[82], F. Marzano[132a], A. Marzin[111], L. Masetti[81], T. Mashimo[155], R. Mashinistov[94], J. Masik[82], A.L. Maslennikov[107], M. Maß[42], I. Massa[19a,19b], G. Massaro[105], N. Massol[4], P. Mastrandrea[132a,132b], A. Mastroberardino[36a,36b], T. Masubuchi[155], M. Mathes[20], P. Matricon[115], H. Matsumoto[155], H. Matsunaga[155], T. Matsushita[67], C. Mattravers[118,c], J.M. Maugain[29], S.J. Maxfield[73], D.A. Maximov[107], E.N. May[5], A. Mayne[139], R. Mazini[151], M. Mazur[20], M. Mazzanti[89a], E. Mazzoni[122a,122b], S.P. Mc Kee[87], A. McCarn[165], R.L. McCarthy[148], T.G. McCarthy[28], N.A. McCubbin[129], K.W. McFarlane[56], J.A. Mcfayden[139], H. McGlone[53], G. Mchedlidze[51], R.A. McLaren[29], T. Mclaughlan[17], S.J. McMahon[129], R.A. McPherson[169,j], A. Meade[84], J. Mechnich[105], M. Mechtel[174], M. Medinnis[41], R. Meera-Lebbai[111], T. Meguro[116], R. Mehdiyev[93], S. Mehlhase[35], A. Mehta[73], K. Meier[58a], J. Meinhardt[48], B. Meirose[79], C. Melachrinos[30], B.R. Mellado Garcia[172], L. Mendoza Navas[162], Z. Meng[151,s], A. Mengarelli[19a,19b], S. Menke[99], C. Menot[29], E. Meoni[11], K.M. Mercurio[57], P. Mermod[118], L. Merola[102a,102b], C. Meroni[89a], F.S. Merritt[30], A. Messina[29], J. Metcalfe[103], A.S. Mete[64], S. Meuser[20], C. Meyer[81], J.-P. Meyer[136], J. Meyer[173], J. Meyer[54], T.C. Meyer[29], W.T. Meyer[64], J. Miao[32d], S. Michal[29], L. Micu[25a], R.P. Middleton[129], P. Miele[29], S. Migas[73], L. Mijović[41], G. Mikenberg[171], M. Mikestikova[125], M. Mikuž[74], D.W. Miller[143], R.J. Miller[88], W.J. Mills[168], C. Mills[57], A. Milov[171], D.A. Milstead[146a,146b], D. Milstein[171], A.A. Minaenko[128], M. Miñano[167], I.A. Minashvili[65], A.I. Mincer[108], B. Mindur[37], M. Mineev[65], Y. Ming[130], L.M. Mir[11], G. Mirabelli[132a], L. Miralles Verge[11], A. Misiejuk[76], J. Mitrevski[137], G.Y. Mitrofanov[128], V.A. Mitsou[167], S. Mitsui[66], P.S. Miyagawa[82], K. Miyazaki[67], J.U. Mjörnmark[79], T. Moa[146a,146b], P. Mockett[138], S. Moed[57], V. Moeller[27], K. Mönig[41], N. Möser[20], S. Mohapatra[148], B. Mohn[13], W. Mohr[48], S. Mohrdieck-Möck[99], A.M. Moisseev[128,*], R. Moles-Valls[167], J. Molina-Perez[29], J. Monk[77], E. Monnier[83], S. Montesano[89a,89b], F. Monticelli[70], S. Monzani[19a,19b], R.W. Moore[2], G.F. Moorhead[86], C. Mora Herrera[49], A. Moraes[53], A. Morais[124a,b], N. Morange[136], J. Morel[54], G. Morello[36a,36b], D. Moreno[81], M. Moreno Llácer[167], P. Morettini[50a], M. Morii[57], J. Morin[75], Y. Morita[66], A.K. Morley[29], G. Mornacchi[29], M.-C. Morone[49], S.V. Morozov[96], J.D. Morris[75], L. Morvaj[101], H.G. Moser[99], M. Mosidze[51], J. Moss[109], R. Mount[143], E. Mountricha[136], S.V. Mouraviev[94], E.J.W. Moyse[84], M. Mudrinic[12b], F. Mueller[58a], J. Mueller[123], K. Mueller[20], T.A. Müller[98], D. Muenstermann[29], A. Muijs[105], A. Muir[168], Y. Munwes[153], K. Murakami[66], W.J. Murray[129], I. Mussche[105], E. Musto[102a,102b], A.G. Myagkov[128], M. Myska[125], J. Nadal[11], K. Nagai[160], K. Nagano[66], Y. Nagasaka[60], A.M. Nairz[29], Y. Nakahama[29], K. Nakamura[155], I. Nakano[110], G. Nanava[20], A. Napier[161], M. Nash[77,c], N.R. Nation[21], T. Nattermann[20], T. Naumann[41], G. Navarro[162], H.A. Neal[87], E. Nebot[80], P.Yu. Nechaeva[94], A. Negri[119a,119b], G. Negri[29], S. Nektarijevic[49], A. Nelson[64], S. Nelson[143], T.K. Nelson[143], S. Nemecek[125], P. Nemethy[108], A.A. Nepomuceno[23a], M. Nessi[29,u], S.Y. Nesterov[121], M.S. Neubauer[165], A. Neusiedl[81], R.M. Neves[108], P. Nevski[24], P.R. Newman[17], R.B. Nickerson[118], R. Nicolaidou[136], L. Nicolas[139], B. Nicquevert[29], F. Niedercorn[115], J. Nielsen[137], T. Niinikoski[29], A. Nikiforov[15], V. Nikolaenko[128], K. Nikolaev[65], I. Nikolic-Audit[78], K. Nikolics[49], K. Nikolopoulos[24], H. Nilsen[48], P. Nilsson[7], Y. Ninomiya[155], A. Nisati[132a], T. Nishiyama[67], R. Nisius[99], L. Nodulman[5], M. Nomachi[116], I. Nomidis[154], M. Nordberg[29], B. Nordkvist[146a,146b], P.R. Norton[129], J. Novakova[126], M. Nozaki[66], M. Nožička[41], L. Nozka[113], I.M. Nugent[159a], A.-E. Nuncio-Quiroz[20], G. Nunes Hanninger[86], T. Nunnemann[98], E. Nurse[77], T. Nyman[29], B.J. O'Brien[45], S.W. O'Neale[17,*], D.C. O'Neil[142], V. O'Shea[53], F.G. Oakham[28,e], H. Oberlack[99], J. Ocariz[78], A. Ochi[67], S. Oda[155], S. Odaka[66], J. Odier[83], H. Ogren[61], A. Oh[82], S.H. Oh[44], C.C. Ohm[146a,146b], T. Ohshima[101], H. Ohshita[140], T.K. Ohska[66], T. Ohsugi[59], S. Okada[67], H. Okawa[163], Y. Okumura[101], T. Okuyama[155], M. Olcese[50a], A.G. Olchevski[65], M. Oliveira[124a,h], D. Oliveira Damazio[24], E. Oliver Garcia[167], D. Olivito[120], A. Olszewski[38], J. Olszowska[38], C. Omachi[67], A. Onofre[124a,v], P.U.E. Onyisi[30], C.J. Oram[159a], M.J. Oreglia[30], Y. Oren[153], D. Orestano[134a,134b], I. Orlov[107], C. Oropeza Barrera[53], R.S. Orr[158], B. Osculati[50a,50b], R. Ospanov[120], C. Osuna[11], G. Otero y Garzon[26], J.P. Ottersbach[105], M. Ouchrif[135d], F. Ould-Saada[117], A. Ouraou[136], Q. Ouyang[32a], M. Owen[82], S. Owen[139], O.K. Øye[13], V.E. Ozcan[18a], N. Ozturk[7], A. Pacheco Pages[11], C. Padilla Aranda[11], S. Pagan Griso[14], E. Paganis[139], F. Paige[24], K. Pajchel[117], S. Palestini[29], D. Pallin[33], A. Palma[124a,b], J.D. Palmer[17], Y.B. Pan[172], E. Panagiotopoulou[9], B. Panes[31a], N. Panikashvili[87], S. Panitkin[24], D. Pantea[25a], M. Panuskova[125], V. Paolone[123], A. Papadelis[146a], Th.D. Papadopoulou[9], A. Paramonov[5], W. Park[24,w], M.A. Parker[27], F. Parodi[50a,50b], J.A. Parsons[34], U. Parzefall[48], E. Pasqualucci[132a], A. Passeri[134a], F. Pastore[134a,134b], Fr. Pastore[29], G. Pásztor[49,x], S. Pataraia[172], N. Patel[150], J.R. Pater[82], S. Patricelli[102a,102b], T. Pauly[29], M. Pecsy[144a], M.I. Pedraza Morales[172], S.V. Peleganchuk[107], H. Peng[172], R. Pengo[29], A. Penson[34], J. Penwell[61], M. Perantoni[23a], K. Perez[34,t], T. Perez Cavalcanti[41], E. Perez Codina[11], M.T. Pérez García-Estañ[167], V. Perez Reale[34], L. Perini[89a,89b], H. Pernegger[29], R. Perrino[72a], P. Perrodo[4], S. Persembe[3a], V.D. Peshekhonov[65], O. Peters[105], B.A. Petersen[29], J. Petersen[29], T.C. Petersen[35], E. Petit[83], A. Petridis[154], C. Petridou[154], E. Petrolo[132a], F. Petrucci[134a,134b], D. Petschull[41], M. Petteni[142], R. Pezoa[31b], A. Phan[86], A.W. Phillips[27], P.W. Phillips[129], G. Piacquadio[29], E. Piccaro[75], M. Piccinini[19a,19b], A. Pickford[53], S.M. Piec[41], R. Piegaia[26], J.E. Pilcher[30], A.D. Pilkington[82], J. Pina[124a,b], M. Pinamonti[164a,164c], A. Pinder[118], J.L. Pinfold[2], J. Ping[32c], B. Pinto[124a,b], O. Pirotte[29], C. Pizio[89a,89b], R. Placakyte[41], M. Plamondon[169], W.G. Plano[82], M.-A. Pleier[24], A.V. Pleskach[128], A. Poblaguev[24], S. Poddar[58a], F. Podlyski[33],

L. Poggioli[115], T. Poghosyan[20], M. Pohl[49], F. Polci[55], G. Polesello[119a], A. Policicchio[138], A. Polini[19a], J. Poll[75], V. Polychronakos[24], D.M. Pomarede[136], D. Pomeroy[22], K. Pommès[29], L. Pontecorvo[132a], B.G. Pope[88], G.A. Popeneciu[25a], D.S. Popovic[12a], A. Poppleton[29], X. Portell Bueso[48], R. Porter[163], C. Posch[21], G.E. Pospelov[99], S. Pospisil[127], I.N. Potrap[99], C.J. Potter[149], C.T. Potter[114], G. Poulard[29], J. Poveda[172], R. Prabhu[77], P. Pralavorio[83], S. Prasad[57], R. Pravahan[7], S. Prell[64], K. Pretzl[16], L. Pribyl[29], D. Price[61], L.E. Price[5], M.J. Price[29], P.M. Prichard[73], D. Prieur[123], M. Primavera[72a], K. Prokofiev[108], F. Prokoshin[31b], S. Protopopescu[24], J. Proudfoot[5], X. Prudent[43], H. Przysiezniak[4], S. Psoroulas[20], E. Ptacek[114], J. Purdham[87], M. Purohit[24,w], P. Puzo[115], Y. Pylypchenko[117], J. Qian[87], Z. Qian[83], Z. Qin[41], A. Quadt[54], D.R. Quarrie[14], W.B. Quayle[172], F. Quinonez[31a], M. Raas[104], V. Radescu[58b], B. Radics[20], T. Rador[18a], F. Ragusa[89a,89b], G. Rahal[177], A.M. Rahimi[109], D. Rahm[24], S. Rajagopalan[24], M. Rammensee[48], M. Rammes[141], M. Ramstedt[146a,146b], K. Randrianarivony[28], P.N. Ratoff[71], F. Rauscher[98], E. Rauter[99], M. Raymond[29], A.L. Read[117], D.M. Rebuzzi[119a,119b], A. Redelbach[173], G. Redlinger[24], R. Reece[120], K. Reeves[40], A. Reichold[105], E. Reinherz-Aronis[153], A. Reinsch[114], I. Reisinger[42], D. Reljic[12a], C. Rembser[29], Z.L. Ren[151], A. Renaud[115], P. Renkel[39], M. Rescigno[132a], S. Resconi[89a], B. Resende[136], P. Reznicek[98], R. Rezvani[158], A. Richards[77], R. Richter[99], E. Richter-Was[38,y], M. Ridel[78], S. Rieke[81], M. Rijpstra[105], M. Rijssenbeek[148], A. Rimoldi[119a,119b], L. Rinaldi[19a], R.R. Rios[39], I. Riu[11], G. Rivoltella[89a,89b], F. Rizatdinova[112], E. Rizvi[75], S.H. Robertson[85,j], A. Robichaud-Veronneau[49], D. Robinson[27], J.E.M. Robinson[77], M. Robinson[114], A. Robson[53], J.G. Rocha de Lima[106], C. Roda[122a,122b], D. Roda Dos Santos[29], S. Rodier[80], D. Rodriguez[162], Y. Rodriguez Garcia[15], A. Roe[54], S. Roe[29], O. Røhne[117], V. Rojo[1], S. Rolli[161], A. Romaniouk[96], V.M. Romanov[65], G. Romeo[26], D. Romero Maltrana[31a], L. Roos[78], E. Ros[167], S. Rosati[132a,132b], K. Rosbach[49], M. Rose[76], G.A. Rosenbaum[158], E.I. Rosenberg[64], P.L. Rosendahl[13], L. Rosselet[49], V. Rossetti[11], E. Rossi[102a,102b], L.P. Rossi[50a], L. Rossi[89a,89b], M. Rotaru[25a], I. Roth[171], J. Rothberg[138], D. Rousseau[115], C.R. Royon[136], A. Rozanov[83], Y. Rozen[152], X. Ruan[115], I. Rubinskiy[41], B. Ruckert[98], N. Ruckstuhl[105], V.I. Rud[97], C. Rudolph[43], G. Rudolph[62], F. Rühr[6], F. Ruggieri[134a,134b], A. Ruiz-Martinez[64], E. Rulikowska-Zarebska[37], V. Rumiantsev[91,*], L. Rumyantsev[65], K. Runge[48], O. Runolfsson[20], Z. Rurikova[48], N.A. Rusakovich[65], D.R. Rust[61], J.P. Rutherfoord[6], C. Ruwiedel[14], P. Ruzicka[125], Y.F. Ryabov[121], V. Ryadovikov[128], P. Ryan[88], M. Rybar[126], G. Rybkin[115], N.C. Ryder[118], S. Rzaeva[10], A.F. Saavedra[150], I. Sadeh[153], H.F.-W. Sadrozinski[137], R. Sadykov[65], F. Safai Tehrani[132a,132b], H. Sakamoto[155], G. Salamanna[75], A. Salamon[133a], M. Saleem[111], D. Salihagic[99], A. Salnikov[143], J. Salt[167], B.M. Salvachua Ferrando[5], D. Salvatore[36a,36b], F. Salvatore[149], A. Salvucci[104], A. Salzburger[29], D. Sampsonidis[154], B.H. Samset[117], A. Sanchez[102a,102b], H. Sandaker[13], H.G. Sander[81], M.P. Sanders[98], M. Sandhoff[174], T. Sandoval[27], R. Sandstroem[99], S. Sandvoss[174], D.P.C. Sankey[129], A. Sansoni[47], C. Santamarina Rios[85], C. Santoni[33], R. Santonico[133a,133b], H. Santos[124a], J.G. Saraiva[124a,b], T. Sarangi[172], E. Sarkisyan-Grinbaum[7], F. Sarri[122a,122b], G. Sartisohn[174], O. Sasaki[66], T. Sasaki[66], N. Sasao[68], I. Satsounkevitch[90], G. Sauvage[4], E. Sauvan[4], J.B. Sauvan[115], P. Savard[158,e], V. Savinov[123], D.O. Savu[29], P. Savva[9], L. Sawyer[24,l], D.H. Saxon[53], L.P. Says[33], C. Sbarra[19a,19b], A. Sbrizzi[19a,19b], O. Scallon[93], D.A. Scannicchio[163], J. Schaarschmidt[115], P. Schacht[99], U. Schäfer[81], S. Schaepe[20], S. Schaetzel[58b], A.C. Schaffer[115], D. Schaile[98], R.D. Schamberger[148], A.G. Schamov[107], V. Scharf[58a], V.A. Schegelsky[121], D. Scheirich[87], M.I. Scherzer[14], C. Schiavi[50a,50b], J. Schieck[98], M. Schioppa[36a,36b], S. Schlenker[29], J.L. Schlereth[5], E. Schmidt[48], K. Schmieden[20], C. Schmitt[81], S. Schmitt[58b], M. Schmitz[20], A. Schöning[58b], M. Schott[29], D. Schouten[142], J. Schovancova[125], M. Schram[85], C. Schroeder[81], N. Schroer[58c], S. Schuh[29], G. Schuler[29], J. Schultes[174], H.-C. Schultz-Coulon[58a], H. Schulz[15], J.W. Schumacher[20], M. Schumacher[48], B.A. Schumm[137], Ph. Schune[136], C. Schwanenberger[82], A. Schwartzman[143], Ph. Schwemling[78], R. Schwienhorst[88], R. Schwierz[43], J. Schwindling[136], T. Schwindt[20], W.G. Scott[129], J. Searcy[114], E. Sedykh[121], E. Segura[11], S.C. Seidel[103], A. Seiden[137], F. Seifert[43], J.M. Seixas[23a], G. Sekhniaidze[102a], D.M. Seliverstov[121], B. Sellden[146a], G. Sellers[73], M. Seman[144b], N. Semprini-Cesari[19a,19b], C. Serfon[98], L. Serin[115], R. Seuster[99], H. Severini[111], M.E. Sevior[86], A. Sfyrla[29], E. Shabalina[54], M. Shamim[114], L.Y. Shan[32a], J.T. Shank[21], Q.T. Shao[86], M. Shapiro[14], P.B. Shatalov[95], L. Shaver[6], C. Shaw[53], K. Shaw[164a,164c], D. Sherman[175], P. Sherwood[77], A. Shibata[108], H. Shichi[101], S. Shimizu[29], M. Shimojima[100], T. Shin[56], A. Shmeleva[94], M.J. Shochet[30], D. Short[118], M.A. Shupe[6], P. Sicho[125], A. Sidoti[132a,132b], A. Siebel[174], F. Siegert[48], J. Siegrist[14], Dj. Sijacki[12a], O. Silbert[171], J. Silva[124a,b], Y. Silver[153], D. Silverstein[143], S.B. Silverstein[146a], V. Simak[127], O. Simard[136], Lj. Simic[12a], S. Simion[115], B. Simmons[77], M. Simonyan[35], P. Sinervo[158], N.B. Sinev[114], V. Sipica[141], G. Siragusa[173], A.N. Sisakyan[65], S.Yu. Sivoklokov[97], J. Sjölin[146a,146b], T.B. Sjursen[13], L.A. Skinnari[14], K. Skovpen[107], P. Skubic[111], N. Skvorodnev[22], M. Slater[17], T. Slavicek[127], K. Sliwa[161], T.J. Sloan[71], J. Sloper[29], V. Smakhtin[171], S.Yu. Smirnov[96], L.N. Smirnova[97], O. Smirnova[79], B.C. Smith[57], D. Smith[143], K.M. Smith[53], M. Smizanska[71], K. Smolek[127], A.A. Snesarev[94], S.W. Snow[82], J. Snow[111], J. Snuverink[105], S. Snyder[24], M. Soares[124a], R. Sobie[169,j], J. Sodomka[127], A. Soffer[153], C.A. Solans[167], M. Solar[127], J. Solc[127], E. Soldatov[96], U. Soldevila[167], E. Solfaroli Camillocci[132a,132b], A.A. Solodkov[128], O.V. Solovyanov[128], J. Sondericker[24], N. Soni[2], V. Sopko[127], B. Sopko[127], M. Sorbi[89a,89b], M. Sosebee[7], A. Soukharev[107], S. Spagnolo[72a,72b], F. Spanò[34], R. Spighi[19a], G. Spigo[29], F. Spila[132a,132b], E. Spiriti[134a], R. Spiwoks[29], M. Spousta[126], T. Spreitzer[158], B. Spurlock[7], R.D.St. Denis[53], T. Stahl[141],

J. Stahlman[120], R. Stamen[58a], E. Stanecka[29], R.W. Stanek[5], C. Stanescu[134a], S. Stapnes[117], E.A. Starchenko[128], J. Stark[55], P. Staroba[125], P. Starovoitov[91], A. Staude[98], P. Stavina[144a], G. Stavropoulos[14], G. Steele[53], P. Steinbach[43], P. Steinberg[24], I. Stekl[127], B. Stelzer[142], H.J. Stelzer[41], O. Stelzer-Chilton[159a], H. Stenzel[52], K. Stevenson[75], G.A. Stewart[29], J.A. Stillings[20], T. Stockmanns[20], M.C. Stockton[29], K. Stoerig[48], G. Stoicea[25a], S. Stonjek[99], P. Strachota[126], A.R. Stradling[7], A. Straessner[43], J. Strandberg[147], S. Strandberg[146a,146b], A. Strandlie[117], M. Strang[109], E. Strauss[143], M. Strauss[111], P. Strizenec[144b], R. Ströhmer[173], D.M. Strom[114], J.A. Strong[76,*], R. Stroynowski[39], J. Strube[129], B. Stugu[13], I. Stumer[24,*], J. Stupak[148], P. Sturm[174], D.A. Soh[151,q], D. Su[143], H.S. Subramania[2], A. Succurro[11], Y. Sugaya[116], T. Sugimoto[101], C. Suhr[106], K. Suita[67], M. Suk[126], V.V. Sulin[94], S. Sultansoy[3d], T. Sumida[29], X. Sun[55], J.E. Sundermann[48], K. Suruliz[139], S. Sushkov[11], G. Susinno[36a,36b], M.R. Sutton[149], Y. Suzuki[66], M. Svatos[125], Yu.M. Sviridov[128], S. Swedish[168], I. Sykora[144a], T. Sykora[126], B. Szeless[29], J. Sánchez[167], D. Ta[105], K. Tackmann[41], A. Taffard[163], R. Tafirout[159a], A. Taga[117], N. Taiblum[153], Y. Takahashi[101], H. Takai[24], R. Takashima[69], H. Takeda[67], T. Takeshita[140], M. Talby[83], A. Talyshev[107], M.C. Tamsett[24], J. Tanaka[155], R. Tanaka[115], S. Tanaka[131], S. Tanaka[66], Y. Tanaka[100], K. Tani[67], N. Tannoury[83], G.P. Tappern[29], S. Tapprogge[81], D. Tardif[158], S. Tarem[152], F. Tarrade[24], G.F. Tartarelli[89a], P. Tas[126], M. Tasevsky[125], E. Tassi[36a,36b], M. Tatarkhanov[14], C. Taylor[77], F.E. Taylor[92], G.N. Taylor[86], W. Taylor[159b], M. Teixeira Dias Castanheira[75], P. Teixeira-Dias[76], K.K. Temming[48], H. Ten Kate[29], P.K. Teng[151], S. Terada[66], K. Terashi[155], J. Terron[80], M. Terwort[41,o], M. Testa[47], R.J. Teuscher[158,j], J. Thadome[174], J. Therhaag[20], T. Theveneaux-Pelzer[78], M. Thioye[175], S. Thoma[48], J.P. Thomas[17], E.N. Thompson[84], P.D. Thompson[17], P.D. Thompson[158], A.S. Thompson[53], E. Thomson[120], M. Thomson[27], R.P. Thun[87], T. Tic[125], V.O. Tikhomirov[94], Y.A. Tikhonov[107], C.J.W.P. Timmermans[104], P. Tipton[175], F.J. Tique Aires Viegas[29], S. Tisserant[83], J. Tobias[48], B. Toczek[37], T. Todorov[4], S. Todorova-Nova[161], B. Toggerson[163], J. Tojo[66], S. Tokár[144a], K. Tokunaga[67], K. Tokushuku[66], K. Tollefson[88], M. Tomoto[101], L. Tompkins[14], K. Toms[103], G. Tong[32a], A. Tonoyan[13], C. Topfel[16], N.D. Topilin[65], I. Torchiani[29], E. Torrence[114], H. Torres[78], E. Torró Pastor[167], J. Toth[83,x], F. Touchard[83], D.R. Tovey[139], D. Traynor[75], T. Trefzger[173], L. Tremblet[29], A. Tricoli[29], I.M. Trigger[159a], S. Trincaz-Duvoid[78], T.N. Trinh[78], M.F. Tripiana[70], W. Trischuk[158], A. Trivedi[24,w], B. Trocmé[55], C. Troncon[89a], M. Trottier-McDonald[142], A. Trzupek[38], C. Tsarouchas[29], J.C.-L. Tseng[118], M. Tsiakiris[105], P.V. Tsiareshka[90], D. Tsionou[4], G. Tsipolitis[9], V. Tsiskaridze[48], E.G. Tskhadadze[51], I.I. Tsukerman[95], V. Tsulaia[14], J.-W. Tsung[20], S. Tsuno[66], D. Tsybychev[148], A. Tua[139], J.M. Tuggle[30], M. Turala[38], D. Turecek[127], I. Turk Cakir[3e], E. Turlay[105], R. Turra[89a,89b], P.M. Tuts[34], A. Tykhonov[74], M. Tylmad[146a,146b], M. Tyndel[129], H. Tyrvainen[29], G. Tzanakos[8], K. Uchida[20], I. Ueda[155], R. Ueno[28], M. Ugland[13], M. Uhlenbrock[20], M. Uhrmacher[54], F. Ukegawa[160], G. Unal[29], D.G. Underwood[5], A. Undrus[24], G. Unel[163], Y. Unno[66], D. Urbaniec[34], E. Urkovsky[153], P. Urrejola[31a], G. Usai[7], M. Uslenghi[119a,119b], L. Vacavant[83], V. Vacek[127], B. Vachon[85], S. Vahsen[14], J. Valenta[125], P. Valente[132a], S. Valentinetti[19a,19b], S. Valkar[126], E. Valladolid Gallego[167], S. Vallecorsa[152], J.A. Valls Ferrer[167], H. van der Graaf[105], E. van der Kraaij[105], R. Van Der Leeuw[105], E. van der Poel[105], D. van der Ster[29], B. Van Eijk[105], N. van Eldik[84], P. van Gemmeren[5], Z. van Kesteren[105], I. van Vulpen[105], W. Vandelli[29], G. Vandoni[29], A. Vaniachine[5], P. Vankov[41], F. Vannucci[78], F. Varela Rodriguez[29], R. Vari[132a], E.W. Varnes[6], D. Varouchas[14], A. Vartapetian[7], K.E. Varvell[150], V.I. Vassilakopoulos[56], F. Vazeille[33], G. Vegni[89a,89b], J.J. Veillet[115], C. Vellidis[8], F. Veloso[124a], R. Veness[29], S. Veneziano[132a], A. Ventura[72a,72b], D. Ventura[138], M. Venturi[48], N. Venturi[16], V. Vercesi[119a], M. Verducci[138], W. Verkerke[105], J.C. Vermeulen[105], A. Vest[43], M.C. Vetterli[142,e], I. Vichou[165], T. Vickey[145b,z], G.H.A. Viehhauser[118], S. Viel[168], M. Villa[19a,19b], M. Villaplana Perez[167], E. Vilucchi[47], M.G. Vincter[28], E. Vinek[29], V.B. 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